NASA TN D-186

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NASA TN D-186

TECHNICAL NOTE

D-186

A FLYING-QUALITIES STUDY OF A SMALL RAM-JET HELICOPTER

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON April 1960

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SUMMARY

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Some flight-test measurements are presented of the handling qualities and stability characteristics of a small helicopter with a gross weight of 1,080 pounds. The helicopter was equipped with blade-tip-mounted ram-jet engines and was cyclicly controlled by a servocontrol rotor.

In general, it was found that the high control powers in roll and pitch existing in this helicopter, in conjunction with increased damping resulting from its tip-mounted engines and control rotor, provided a desirable combination of handling qualities for this size of helicopter. However, these otherwise good qualities were often obscured by a neutrally damped short-period fuselage oscillation (0.8 cycle/sec) which existed during all flight conditions and often opposed the aircraft response to control.

Blade-tip-mounted ram-jet engines as sources of high rotor inertia were found to provide stored-rotor-energy characteristics which safely allowed power cuts from hovering at skid heights up to at least 15 feet. The high-energy rotor was such that, under favorable test conditions, high rates of descent at low power can be checked readily without excessive loss in rotor rotational speed. Under actual emergency conditions, with no power, the ratio of available rotor energy to descent energy might be inadequate to compensate safely for errors in judgment. High rotor energy is obtained by the added rotor inertia, and if rotor rotational speed should drop excessively, too much time might be required to return to an adequate rotor speed for completion of a safe landing.

INTRODUCTION

As an extension of previous work by the National Aeronautics and Space Administration on helicopter flying qualities to smaller size machines, a flight investigation utilizing a very small helicopter was undertaken. Its maximum gross weight of 1,080 pounds is less than half the gross weight of any helicopter for which the handling qualities have been previously studied by the NASA. The results of this study will be of particular value in establishing criteria for desirable flying qualities for very small helicopters. It was also believed that the high-inertia rotor inherent with the tip-propulsion system might provide insight to the stability and control characteristics that arise with this type of power source. A brief description is presented of the stability and handling characteristics that could be evaluated without extensive instrumentation.

SYMBOLS

a slope of section lift coefficient against section angle of attack, radians L

a_n normal acceleration, g units 6 4 4

B tip-loss factor; blade elements outboard of radius of rotor blade are assumed to have profile drag but not lift

b' projection of angle between rotor resultant force vector and axis of no feathering in the plane containing the axis of no feathering and perpendicular to the plane containing flight path and axis of no feathering, radians

C_T rotor thrust coefficient, $\frac{T}{\pi R^2 \rho (\Omega R)^2}$

c blade-section chord, ft

g acceleration due to gravity

$\frac{\Delta b'}{p}$ damping factor, or the lateral tilt of rotor resultant force vector per unit rolling velocity, sec

I_1 mass moment of inertia of blade about flapping hinge, slug-ft^2

p rolling angular velocity, radians/sec

q pitching angular velocity, radians/sec

R blade radius to center line of engine, ft

r yawing angular velocity, radians/sec

T thrust, lb

V true airspeed of helicopter along flight path, ft/sec unless otherwise specified

α rotor angle of attack; angle between flight path and plane perpendicular to axis of no feathering, positive when axis is pointing rearward, radians

γ mass constant of rotor blade; expresses ratio of air forces to inertia forces, $\frac{\rho c a R^4}{I_1}$

γ_m mass constant of main rotor blade

γ_s mass constant of servocontrol rotor blade

θ blade-section pitch angle; angle between line of zero lift of blade section and plane perpendicular to axis of no feathering (sometimes referred to as collective pitch), radians unless otherwise specified

μ tip-speed ratio, $\frac{V \cos \alpha}{\Omega R}$

μ_m tip-speed ratio of main rotor blade

μ_s tip-speed ratio of servocontrol rotor blade

ρ mass density of air, slugs/cu ft

σ rotor solidity, blade area divided by disk area

Ω rotor angular velocity, radians/sec

Subscript:

max maximum

Total control travel is 50 percent in each direction from the center.

TEST HELICOPTER AND INSTRUMENTATION

The test helicopter is shown in figure 1(a), and its dimensions and physical characteristics are listed in table I. The helicopter has conventional pilot controls, with the cyclic control of the main rotor acting through a servocontrol rotor. The main rotor feeds back flapping angle through its linkage to the servocontrol rotor at a ratio of 1.0 to 1.6 and effectively reduces the control input to 0.625. Collective pitch of the main rotor blades is controlled directly through mechanical linkage. A fixed horizontal tail was located 8.8 feet rearward of the center of gravity.

The instrumentation consisted of standard NASA recorders equipped with synchronized timers installed as shown in figure 1(b). The variables measured were airspeed, pressure altitude, rotor rotational speed, and normal acceleration. Pilot control positions and angular velocities
about the principal inertia axes were also measured; however, these L
measurements were limited by weight and space restrictions to angular 6
velocity about only one axis and to control positions about two axes per 4
flight. 4

FUSELAGE OSCILLATION

A small, continuous fuselage oscillation, neutrally damped in level flight and magnified by ordinary control motion in pitch and roll, was observed throughout the tests. A similar type of oscillation was observed in reference 1 in which the swashplate and cylic control stick of the test helicopter were flexibly connected. An oscillatory mode of the same frequency can also be calculated for the rotor system of the helicopter but the predicted rotor oscillation does not fully account for the amplified fuselage oscillation.

A rigorous analysis of the fuselage oscillation is not within the scope of this paper but its existence could not be overlooked during the flying-qualities assessment of the test helicopter, however a conscious attempt has been made to evaluate the handling qualities of the helicopter as they would be in the absence of the oscillation. In certain cases, however, this oscillation was the major factor contributing to the pilots' opinions. In such cases, the effects of the oscillation are discussed in detail.

LATERAL-DIRECTIONAL FLYING QUALITIES

Roll Characteristics

Oscillatory roll velocity.- Typical time histories of two pedal-fixed roll maneuvers, one left and one right, are shown in figure 2. In both cases, the resulting angular velocity is oscillatory. The small continuous oscillation has a frequency of about 0.8 cycle/sec. Because of its small amplitude, the oscillation was of no particular consequence during level flight; however, in some cases the first few cycles of the oscillation following a control input were large enough to reduce the angular velocity momentarily to nearly zero. Under these circumstances, the oscillatory response contributed adversely to the handling qualities in that the pilot was not able to anticipate the eventual response in the first second or so after a control displacement.

Roll damping.- Damping-in-roll measurements were made from several flight records similar to those shown in figure 2. These measured damping values are plotted as a function of power condition and the results are shown in figure 3. A comparison of the measured values with values predicted for this rotor configuration by the method of reference 2 shows that the measured values generally agree with the predicted damping.

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The equation for the calculated curve of figure 3 is

$$\frac{\Delta b'}{p} = \frac{3}{2}\left(1.0 - 0.29\,\frac{\theta}{C_T/\sigma}\right)\frac{\dfrac{16/B^4}{\gamma_m\Omega\left(1 + \dfrac{\mu_m{}^2}{2B^2}\right)} + \dfrac{4/B^4}{\gamma_s\Omega\left(1 + \dfrac{\mu_s{}^2}{2B^2}\right)}}{1.6}$$

The term

$$\frac{4/B^4}{\gamma_s\Omega\left(1 + \dfrac{\mu_s{}^2}{2B^2}\right)}$$

has been added to account for the servocontrol rotor, and the factor 1.6 accounts for the feedback between the main rotor and the servocontrol rotor. The measured damping values are approximately double those of helicopters which have more than twice its gross weight. Furthermore, the high damping tends to prevent overcontrolling which is often encountered in small conventional helicopters. Pilots' comments indicated, however, that because of the oscillation superimposed on the normal response to control, handling-qualities benefits generally associated with higher damping were sometimes difficult to assess.

Roll-pitch coupling.- Roll-pitch coupling effects in the test helicopter were pitchup in left roll and pitchdown in right roll. Longitudinally, coupling in a cyclic pullup caused the helicopter to roll to the right; furthermore, if the maneuver was sustained a yaw velocity developed. The direction of the coupling is the same with respect to the direction of rotor rotation as that encountered in helicopters previously studied. The test helicopter, having almost equal inertia in roll and pitch, experiences similar coupling effects about both roll and pitch axes.

The pilots reported that half as much longitudinal control as lateral cyclic control was required to produce pure roll response during maneuvering flight. A similar correction is required in a longitudinal maneuver to produce pure pitch response. Although all helicopters exhibit some coupling because of gyroscopic forces which arise when the rotor is tilted, linkage refinements in the test helicopter to reduce coupling would result in better flying qualities.

Yaw Characteristics

Figure 4 is a typical time history of a pedal-kick, displace-and-return maneuver. The helicopter oscillated between 30° and 40° in each direction through several cycles with no indication of damping to a fixed heading. In one particular application of this same maneuver, at a forward velocity below 20 knots, the helicopter changed heading by 180°.

The pilots stated that a pedal centering device would improve the handling characteristics by providing a feel force to help them locate the trim position.

LONGITUDINAL FLYING QUALITIES

Maneuver Characteristics

Pull-and-hold maneuver.- A pull-and-hold maneuver is the test customarily employed to determine the flying qualities and handling characteristics related to a helicopter's maneuver stability. The pilots' comments indicated that maneuver stability was satisfactory, and the helicopter showed no tendency to "dig in." ("Digging in" is a term applied to a continued, unwanted angular acceleration about the pitch axis.) The normal-acceleration curve related to the pull-and-hold maneuver was concave downward within 2 seconds, a necessary but not sufficient condition for satisfactory maneuver stability.

A typical time history of a pull-and-hold maneuver is shown in figure 5. If the oscillation which is also amplified in this axis is ignored, the angular velocity becomes constant concurrently with the concaving downward of the normal-acceleration curve. As mentioned previously, the angular-velocity-curve shape augments the normal-acceleration curve in defining satisfactory maneuver stability.

Longitudinal pulse maneuver.- A time history of a longitudinal pulse input is shown in figure 6. The pitching oscillation resulting from this maneuver damped to half-amplitude within 1/2 cycle. Several pulse inputs of this type were executed and all pitch oscillations damped to half-amplitude in periods ranging from 1/4 to 1 cycle. The frequency of the pitch oscillation remained unchanged from that of the residual oscillation (approximately 0.8 cycle/sec). Flying qualities are considered satisfactory when an oscillation caused by a pulse input damps to half-amplitude within 2 cycles.

Speed Stability

Figure 7 is a plot of longitudinal control position against indicated airspeed. This figure shows the speed-stability characteristics of this helicopter to be slightly positive from 10 to 25 knots, slightly negative from 25 to 40 knots, neither positive nor negative from 40 to 50 knots, and positive again above 50 knots. Throughout the speed range the helicopter does not exhibit strong stable or unstable characteristics. This is fairly typical of helicopters and was not considered detrimental by the pilots.

Flare Recovery

Two low-power-descent time histories are presented in figure 8. Figure 8(a) shows a recovery in which the aircraft response to control was quick and positive. In this case the handling characteristics were considered good. Figure 8(b) shows a recovery in which the response to control was sluggish and a large amount of forward control was required for a relatively long time in order to complete the maneuver. The handling characteristics in this recovery were considered unsatisfactory. One reason for this disparity between handling qualities in the same maneuver appears to be cyclic control phasing with the amplified oscillation. When control moment is applied in phase with the oscillation, response is immediate. Conversely, control application out of phase with the oscillation results in a sluggish response. The high ratio of control power to inertia inherent in this helicopter helps somewhat by providing enough power to override the effects of the amplified oscillatory angular velocity.

Autorotative Handling Qualities

Stored rotor energy.- The engines were set at idle burning and collective pitch was set to about -5° in order to obtain conditions close to autorotative descents. Rates of descent in excess of 3,000 ft/min were noted at these low-power conditions. Under these conditions the stored rotor energy was sufficient to halt the descent and to give the pilot time to maneuver to a safe landing without excessive loss in rotor speed. The stored rotor energy is a result of the engine weight (12 pounds) at the blade tips.

The tests indicated that rates of descent well in excess of 3,500 ft/min would occur during emergency conditions with completely cold engines. If the rotor rotational speed should be allowed to drop to a low value during the descent, the ratio of available energy to descent energy might not be adequate for the pilot to maneuver to a safe landing. In this connection, one consideration is that the high-rotor inertia plus the drag of the engines adds to the time required to regain rotational speed if it is once lost. Thus, although the rotor usually lost its energy at a very slow rate, it also regained its rotational speed at a very slow rate.

In order to investigate further the stored energy of the rotor, power was cut in hovering flight at skid heights up to 15 feet. The pilots believed the landing impact would be too severe from above 15 feet, but it would be acceptable up to that altitude.

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A comparison was made by executing this same maneuver in another small helicopter which utilizes a standard rotor and propulsion system. In the alternate helicopter the pilots became apprehensive of the landing impact when the skid height exceeded about 5 feet for this maneuver.

CONTROL POWER AND DAMPING

Reference 3 shows that good flying qualities are dependent in part upon the combination of the ratios of control power to inertia and of damping to inertia for a given helicopter. A criterion which demonstrates the effect of these items is the angular displacement of the aircraft in 1 second brought about by 1 inch of control motion. The flying-qualities factors of control power, damping, inertias about the principal axes, and the angular displacements after 1 second for the test helicopter are summarized in table II. The first three factors were measured and the angular displacements were calculated by assuming a single-degree-of-freedom system with damping.

The ratios of control power to inertia and of damping to inertia about the roll and pitch axes are greater than any encountered in helicopters previously studied for flying qualities. The effects of these high ratios did not appear to be too great, and, in fact, were considered by the pilots to contribute considerably to the generally desirable handling qualities in roll and pitch exhibited by this machine. These results may suggest that, in order to achieve good flying qualities, small helicopters may require higher than ordinary control power and damping. Thus, as suggested in reference 3, boundaries of the type presented in that reference apparently will differ appreciably for very small helicopters as compared with those for medium or large helicopters. The ratio of yaw damping to inertia is somewhat less than the ratio of damping to inertia for pitch and roll, and the directional characteristics are marginal.

CONCLUSIONS

A flight investigation of a small helicopter provided additional flying-qualities information with particular regard to helicopters of its size. Its maximum gross weight of 1,080 pounds is about half the gross weight of the smallest helicopter previously tested. Pilots' opinions indicated that, for this small helicopter, the control power and the damping values which were proportionately higher than those generally found in medium and heavy helicopters contributed favorably toward good flying qualities and handling characteristics. In addition, the following conclusions should be of value in studies of the effect of the size of helicopter on desired characteristics:

1. Damping in pitch and roll is greater than that of any helicopter previously tested, apparently a result of the high rotor-blade inertia and the control rotor. The high damping appears to be very beneficial from flying-qualities considerations and, in particular, tends to prevent overcontrolling which is often encountered with small helicopters.

2. Damping in yaw was considered weak by the pilots, and the disappearance of static directional stability at low speeds was considered a highly adverse characteristic.

3. Speed stability was fairly typical of a helicopter, slightly stable at the upper and lower speed ranges and slightly unstable to neutrally stable in the middle of the speed range.

4. Longitudinal handling characteristics were generally satisfactory. Pulse inputs damped to half-amplitude within 1 cycle or less. From a step input the normal-acceleration curve became concave downward in less than 2 seconds.

5. The good flying qualities, which are attributed to the higher than ordinary damping and control power in pitch and roll, were frequently very nearly obscured by oscillatory angular velocities. For both the pitch and roll axes, a neutrally damped residual oscillation became magnified by normal control motions in ordinary maneuvers. In flare maneuvers the aircraft response to control appeared to depend upon control phasing with the oscillation.

6. Under favorable test conditions, the offsetting effects of higher tip drag and rotor inertia, both resulting from the engine weight at the blade tips, were satisfactory with respect to stored rotor energy during autorotations performed with the engines at idle burning. Stored

energy was considered better than average when power was cut at a skid height of 15 feet.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., September 2, 1959.

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2. Amer, Kenneth B.: Theory of Helicopter Damping in Pitch or Roll and a Comparison With Flight Measurements. NACA TN 2136, 1950.

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TABLE I.- PRINCIPAL CHARACTERISTICS OF HELICOPTER

Normal gross weight, lb	1,080
Weight, empty, lb	544
Useful load, lb	535
Flight-test load, lb:	
Pilot	190
NASA instruments	165
Fuel	180
Total	535
Fuel capacity, lb	300
Normal fuel consumption, lb/hr	790
V_{max}, knots	52
V_{cruise}, knots	43
Rate of climb, normal, ft/min	500
Rate of descent, normal, ft/min	2,400
Pitching moment of inertia, slug-ft^2	167
Rolling moment of inertia, slug-ft^2	156
Yawing moment of inertia, slug-ft^2	66
Engines	Two ram jets, rated at 39 pounds thrust each at cruise rpm
Main rotor:	
Radius, ft	11.83
Chord (constant), ft	0.79
Section and thickness (constant)	NACA 0012
Blade area, sq ft	18.2
Disk area, sq ft	415.0
Solidity	0.044
Blade pitching moment of inertia (one blade, one engine), slug-ft^2	0.116
Blade flapping moment of inertia (one blade, one engine), slug-ft^2	106.7
Blade mass constant, γ (one blade)	1.74
Tip speed, ΩR, ft/sec	680
Preconing angle, deg	1
Collective pitch, deg	-5 to 16.5
Cyclic pitch (lateral and longitudinal), deg	±10
Cyclic control-stick travel, in.	
Longitudinal	8
Lateral	9.75
Servocontrol rotor:	
Radius, ft	3.75
Blade flapping moment of inertia, slug-ft^2	0.73
Blade mass constant	0.176
Tip speed, ft/sec	216
Collective pitch	Fixed
Cyclic pitch, deg	±16
Feedback ratio from main rotor	1.6:1
Tail rotor:	
Radius, ft	1.33
Chord (constant), ft	0.29
Section and thickness (constant)	NACA 0015
Blade area, sq ft	0.39
Disk area, sq ft	5.58
Solidity	0.07
Tip speed, ft/sec	500
Flapping hinge angle, deg	45
Distance from tail-rotor center line to main-rotor center line, ft	6.96
Collective pitch, deg	-19 to 16
Total pedal travel, in.	6.5
Horizontal tail:	
Area, sq ft	3.75
Arm, ft	8.79

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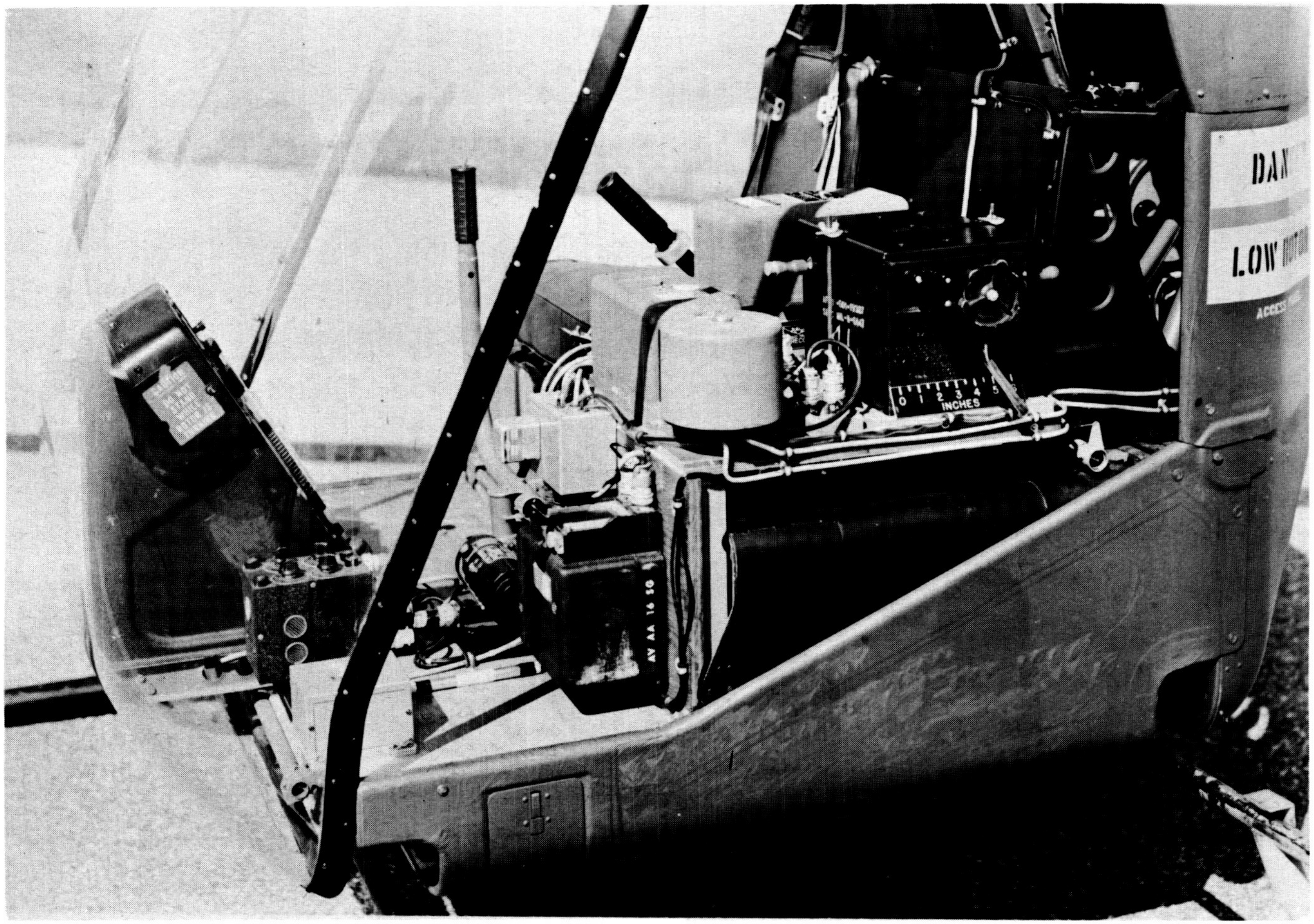
TABLE II.- FLYING-QUALITIES FACTORS

[Gross weight of test helicopter, 1,080 pounds]

Control axis	Pitch	Roll	Yaw
Control moment per inch deflection, ft-lb/in. . . .	109	109	45.8
Damping moment measured from hovering, ft-lb-sec	925	925	108.3
Inertia about principal axes, slug-ft^2	167	156	66
Angular displacement in first second per inch control motion, deg	5.6	5.6	12.3

(a) Test helicopter in delivered configuration. L-57-3948

Figure 1.- Test helicopter.



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(b) Test helicopter with instrumentation installed in copilot's position.

Figure 1.- Concluded.

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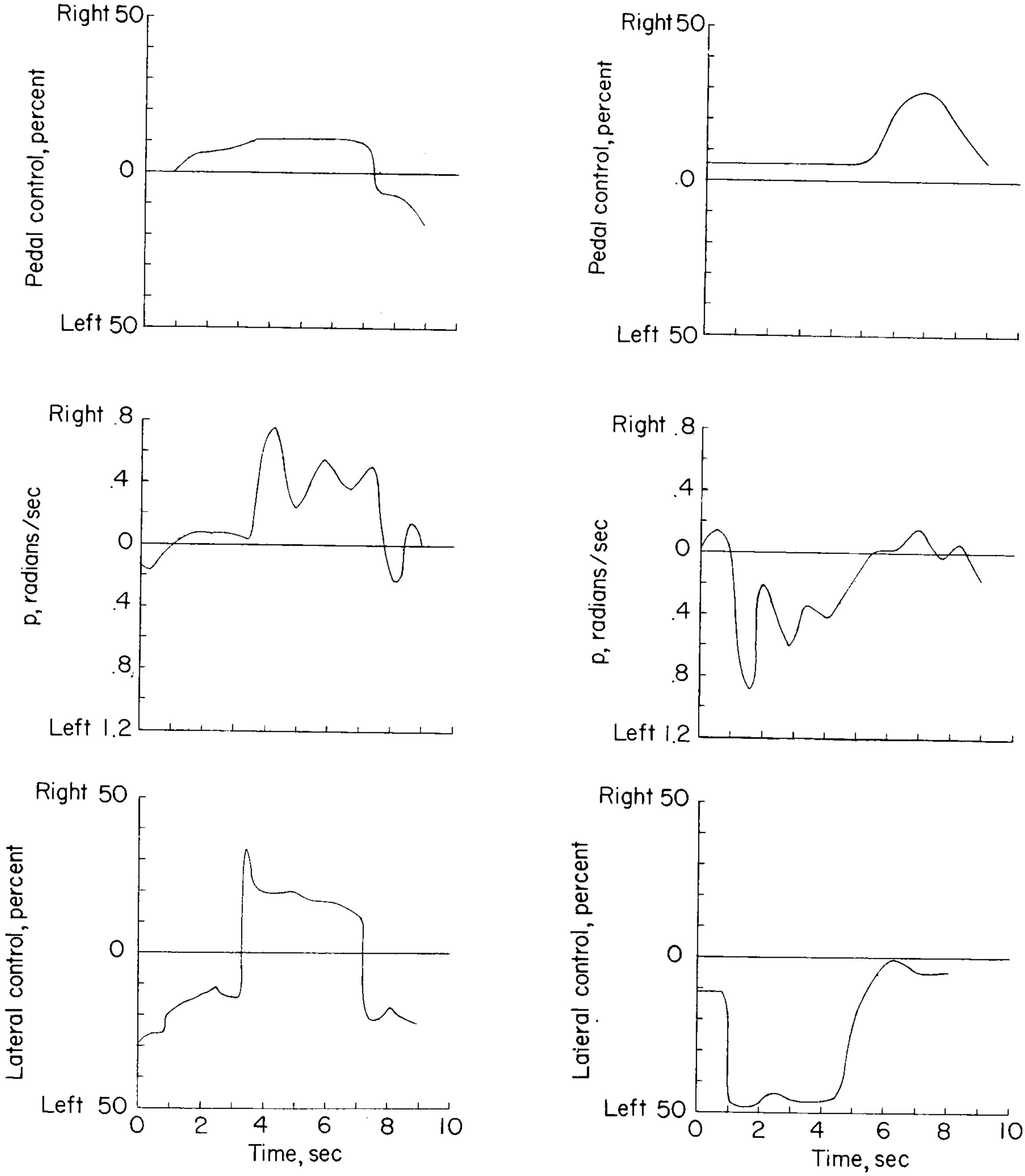

(a) Right roll at 25 knots. (b) Left roll at 35 knots.

Figure 2.- Time histories of typical pedal-fixed roll maneuvers.

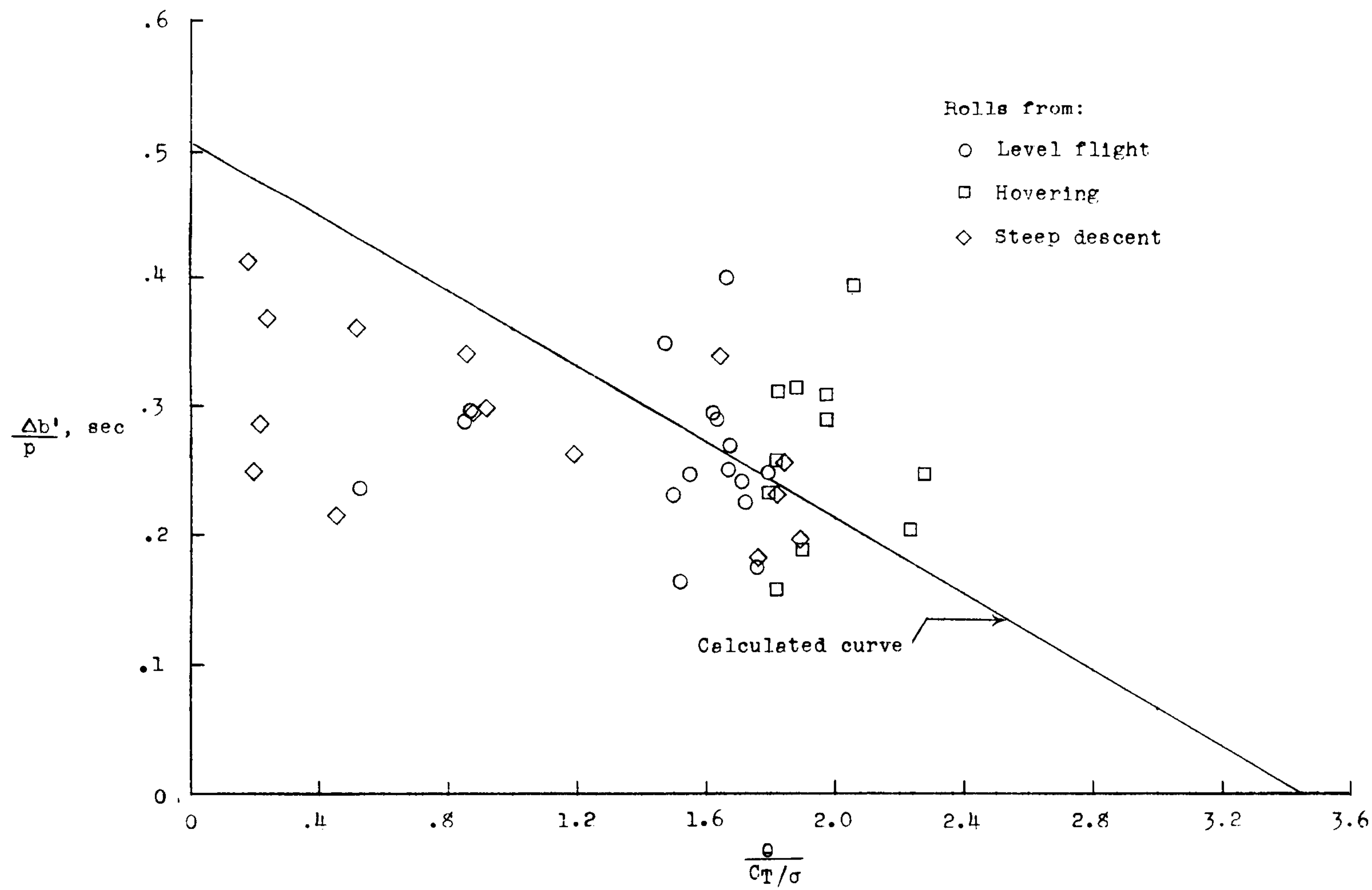

Figure 3.- Plot of damping-in-roll measurements compared with a theoretical curve predicted for test helicopter.

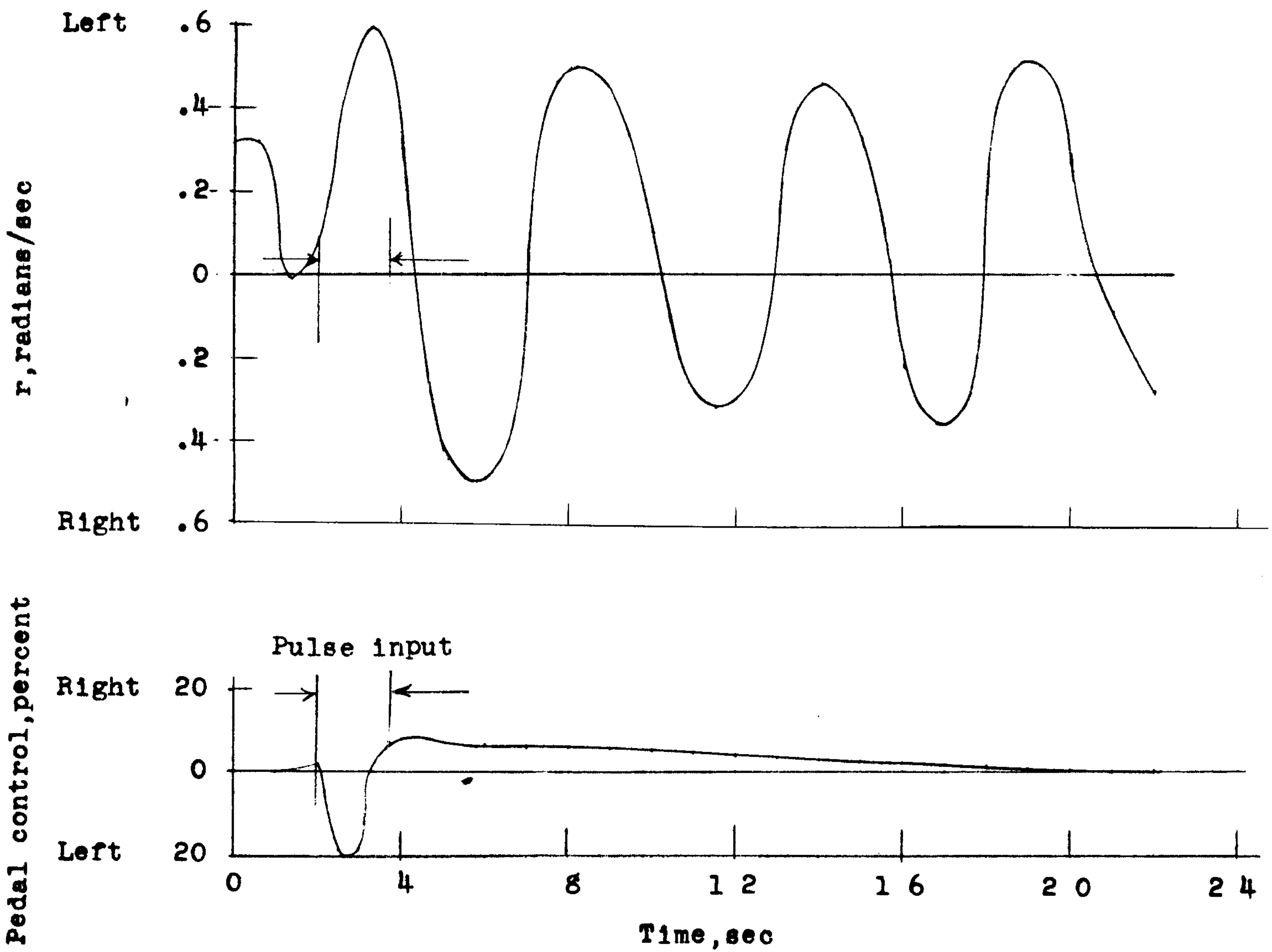

Figure 4.- Time history of a typical pedal-kick pulse input at an indicated airspeed of 40 knots.

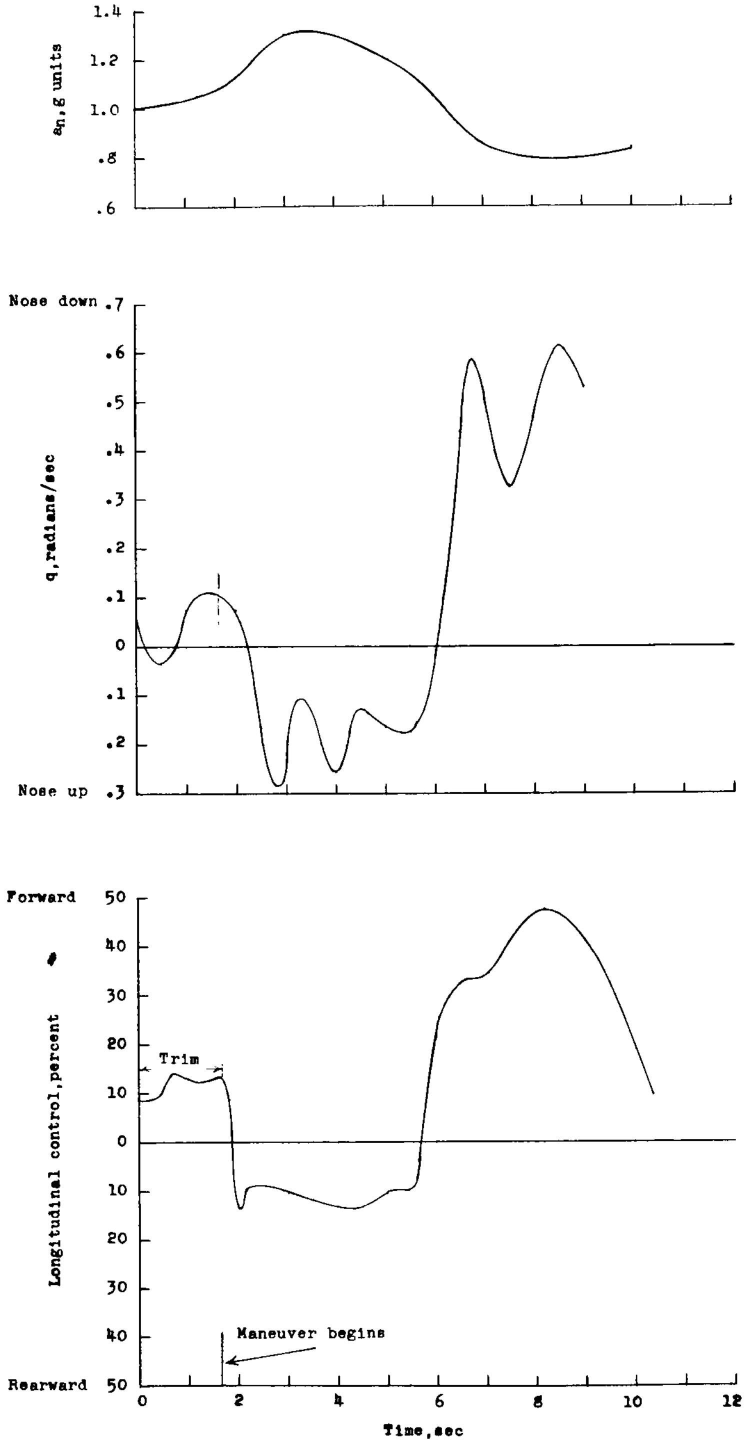

Figure 5.- Pull-and-hold-maneuver time history at an indicated airspeed of 45 knots.

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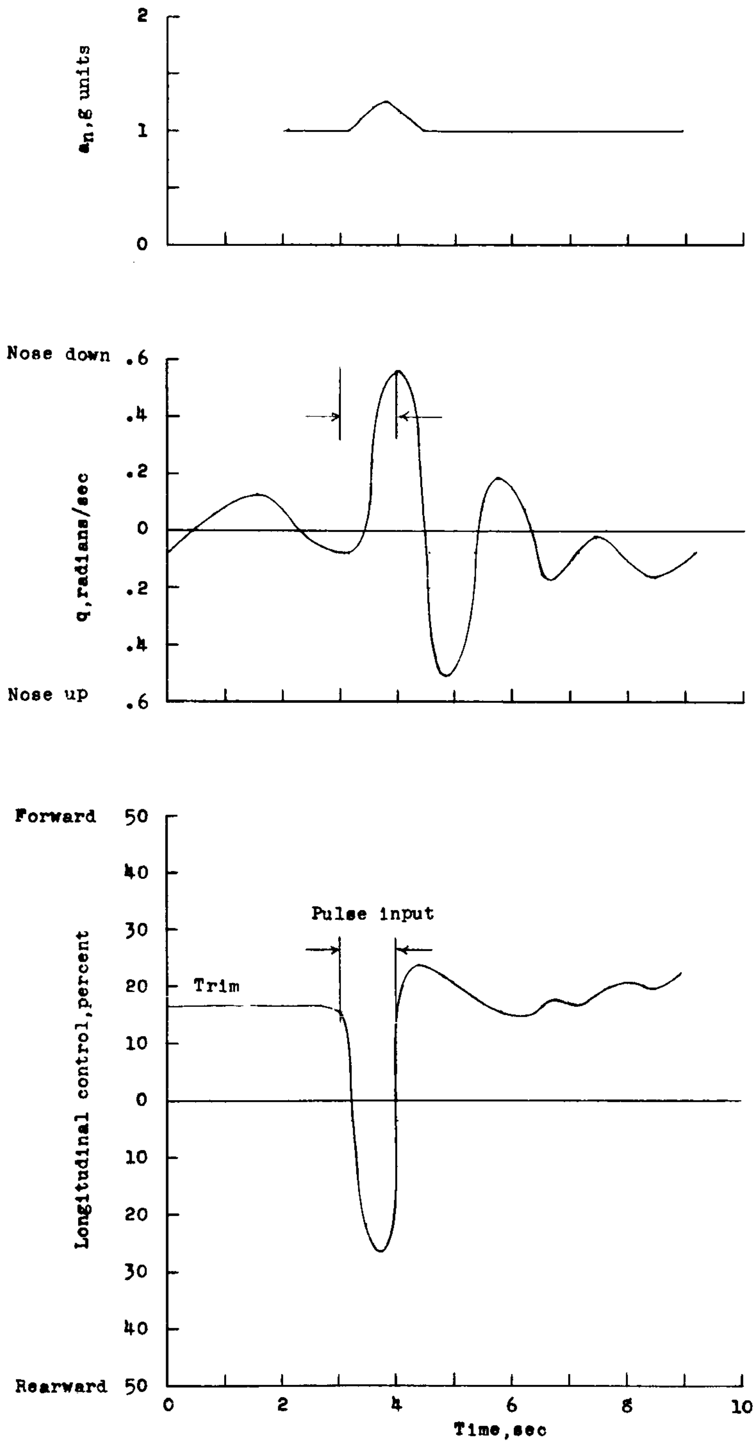

Figure 6.- Longitudinal-pulse-input time history at an indicated airspeed of 35 knots.

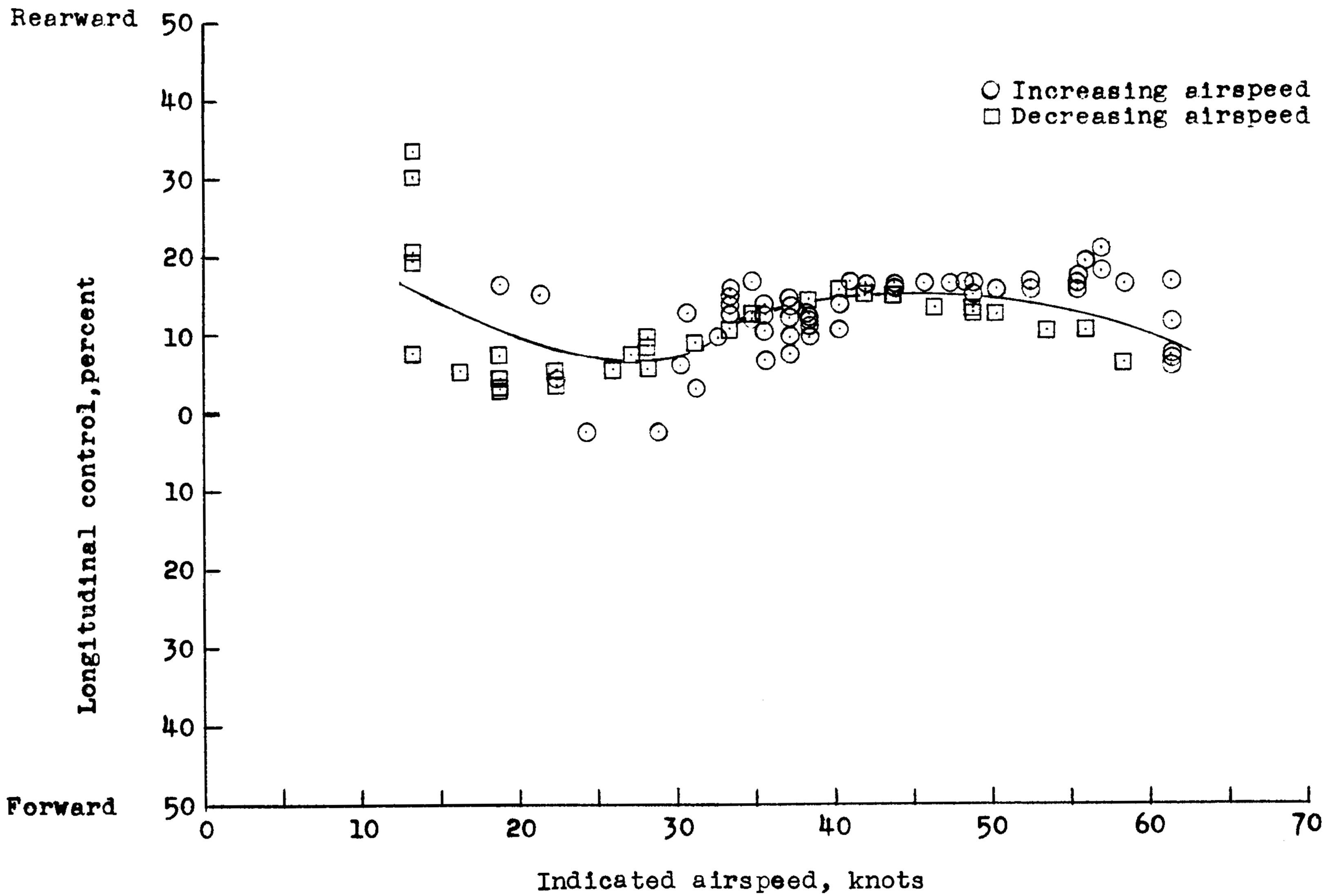

Figure 7.- Speed-stability plot.

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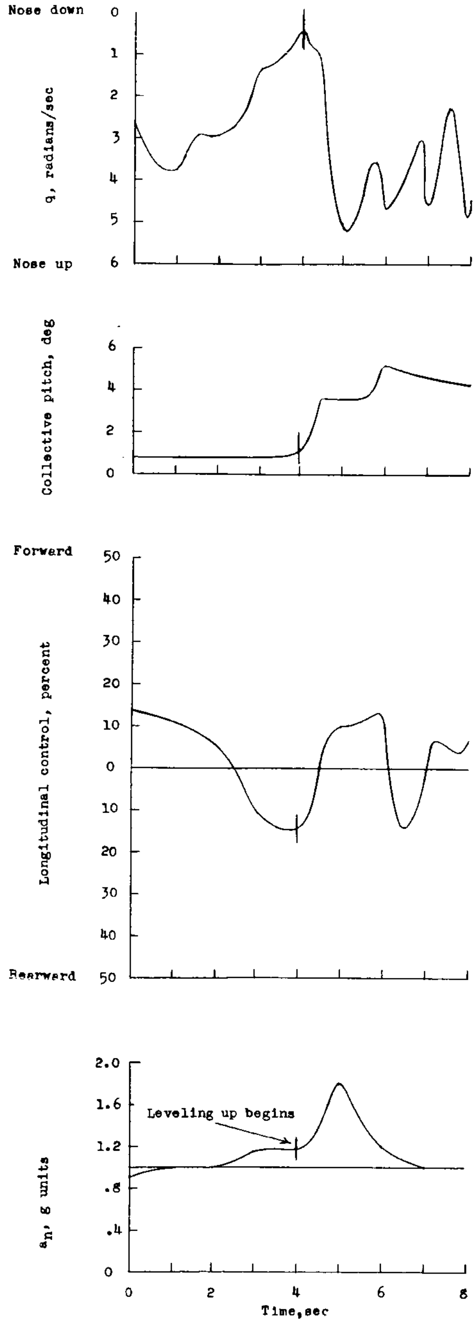
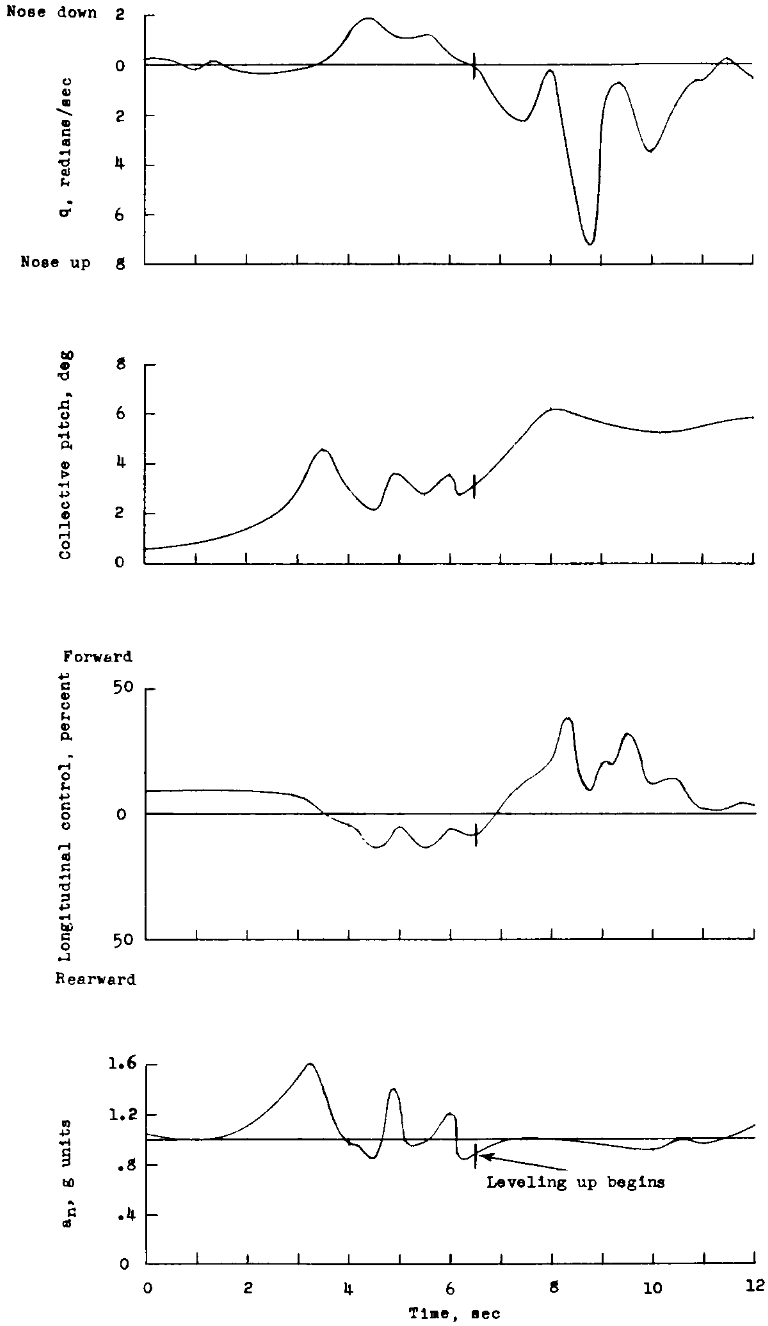


(a) Recovery in which forward longitudinal-control response was judged to be good by the pilots.

Figure 8.- Low-power-descent time histories.



(b) Recovery in which forward longitudinal-control response was judged to be marginal by the pilots.

Figure 8.- Concluded.

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